59th ILMENAU SCIENTIFIC COLLOQUIUM
Technische Universität Ilmenau, 11 – 15 September 2017
URN: urn:nbn:de:gbv:ilm1-2017iwk-088:9

INNOVATIVE FREEFORM MEASUREMENT METHOD USING TWO DIMENSIONAL BINARY DIFFRACTIVE GRATING BASED ON NANOSTRUCTURED SILICON

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ABSTRACT

An innovative metrological method for freeform characterization in transmission as well as in reflection has been developed. The approach is based on diffraction theory and Fourier analysis with modified angular spectrum propagator. We analyze the propagation of a wavefront behind a two-dimensional cross grating and derive a universal method to measure the phase gradient directly from the recorded intensity distribution. This method works for arbitrary distances behind the grating. To prevent unwanted reflection while measuring in reflection and in transmission we use a two dimensional cross grating based on nanostructured black silicon. Our new formulation has been tested successfully through simulations. The wavefront generated by a freeform surface was measured with the new method. The experimental results are verified with a commercial Shack- Hartmann wavefront sensor.

Index Terms - Metrology; Testing; Metrological instrumentation.

1. INTRODUCTION

There is a great need for accurate wavefront and shape measurement in various fields and applications, e.g. in optical measurement technology, industrial production, etc. The rapid development in these areas, particularly in the field of free-form optics, requires new advanced methods and sensors for wavefront measurements with high resolution and accuracy at short measuring times [1] [2].

Freeform surfaces are non-rotationally symmetrical surfaces which have advantages over conventional rotationally symmetric optics, e.g. they offer more degrees of freedom in the design and a higher functional diversity for the optical system [3]. This enables better control of the imaging aberrations and the development of compact and lightweight systems. Therefore, these forms are already used in various fields: e.g. in compact projection systems, head-up displays and lithography [4].

In addition to these numerous advantages, there are still many challenges related to the production and characterization of these surfaces. Nowadays more precise and expensive CNC production machines are used for the production of freeform surfaces [5].

In order to minimize wastage, an immediate control of the production quality is still desirable during fabrication. The reduction of the dimensions of the test equipment simplifies the integration into fabrication machine (e.g. a CNC ultraprecision diamond turning machine)

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For the detection of the shape or wavefront of optically smooth surfaces, there exists a wide range of methods that allow a three-dimensional metrology. The most widely used techniques are contact or tactile coordinate measuring machines, the application of which is to measure a complex surface. However, these are limited in the spatial resolution. Another disadvantage is the long measuring time. In order to achieve reasonable results, a vibration-free environment must be guaranteed. Therefore, these measurement methods are used only for the characterization of samples and integration into a CNC machine is only possible to a limited extent [4].

Other measuring methods use the properties of light as an electromagnetic wave to measure the surface or waves. The test object is illuminated and the light reflected at its surface is recorded and analyzed using various principles (e.g. interferometrically). In this case the measuring system or their assemblies must not be positioned in the beam path of the illumination system since in this case the test object or a part of the optical components is obscured (Fig 1).

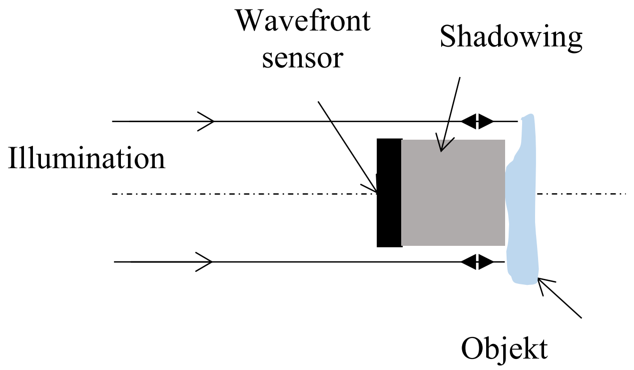

Fig. 1: (a) Schematic representation of the challenge

This problem is circumvented in practice by the use of beam splitters or a slightly inclined illumination of the reflecting test object [Fig. 2]. These variants lead to an increase in the complexity of the measuring devices.. Here we provide an alternative solution to this problem. The result is a measuring arrangement which is compact and can extend the measuring range of the surface gradients almost arbitrarily without requiring any mechanical movements or adjustment during the measuring process. Furthermore, this method allows one to measure in transmission as in reflection.

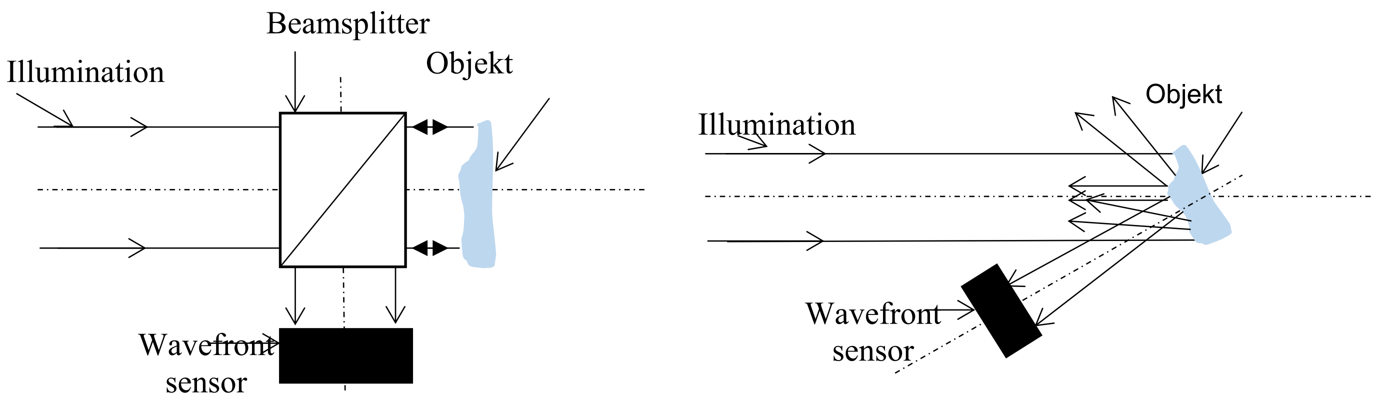

Fig. 2: Conventional solution

In [6] and [7] we presented a novel principle of a wavefront sensor. This is based on diffraction theory and Fourier analysis with a modified angular spectrum propagator. We observe the propagation of a wavefront behind a two-dimensional cross-grid. Using a 4f telescope system with a suitable filter in the Fourier space, we subtract the intensity distribution behind the grating to the level of a CCD camera. In order to reconstruct the wavefront, the recorded intensity image is analyzed in the spectral range. The phase gradients of the measured wavefront are extracted directly from a recorded intensity image.

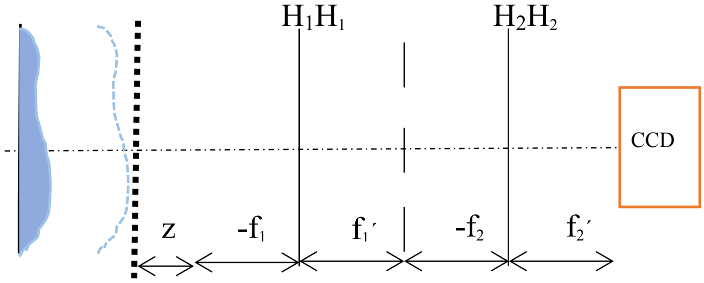

Fig.3 The schematic diagram of the proposed wavefront sensor in transmission.

In this work we extend the measurement setup in such a way that we are able to measure both in reflection and in transmission.
A nanostructured amplitude grating is placed between two 4f systems. In the object-side focal plane of the first optics of the 4f system, an LED with a pinhole is positioned. In the (LED) image plane, a spatial filter only passes through the 0th order. The measurement object is positioned in the image-side plane of the second 4f system. (See Fig. 4).

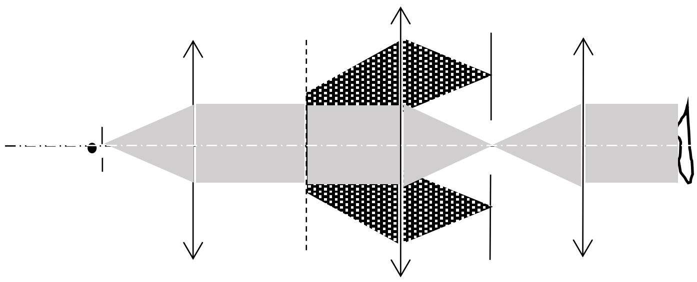

Fig.4 The schematic diagram of the illumination of the proposed wavefront sensor in reflection.

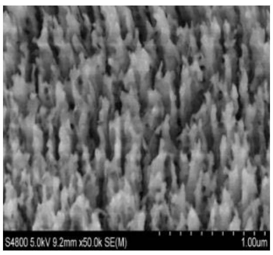

Fig 5 Surface of the black silicon grating under electron microscope

The path of the reflected beam to the pick-up sensor is shown schematically in Fig.6. The plane behind the object to be measured and the amplitude grating are optically conjugate with one another. The space filter leaves only a restricted range of the angular spectrum of the test specimen. Behind the grating in the direction of the camera, only the first orders are passed through a second spatial filter and then interfere in the CCD plane.

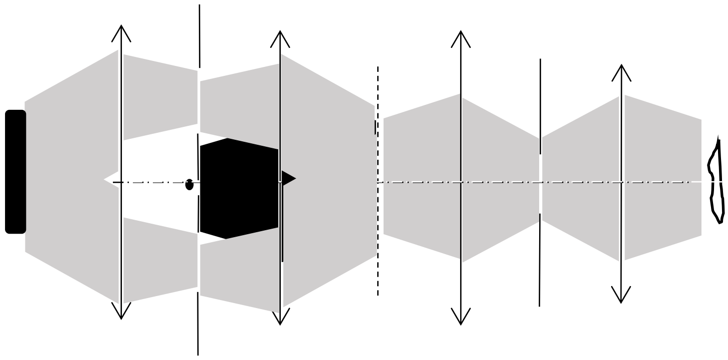

Fig. 6 Schematic diagram of the reflection path wavefront

2. EFFECTIVE EVALUATION OF LIGHT INFORMATION AND SIGNAL PROCESSING

In this section we discuss the effective way to increase the signal to noise ratio by reducing the information content of the light wave captured by the CCD sensor.
The periodic structure of the cross grating leads to replica in the spectral domain, i.e. the same information is replicated over the whole area of spatial frequencies. In our presented algorithm only one spectral replica is required to reconstruct the wavefront gradients. The main challenge is to separate properly the appropriate replica which needs the lowest efforts on processing. This is demonstrated in [6]. The transfer function of the cross grating is given by

$$\tilde{\tau}_f(\omega_x, \omega_y) = \sum_{q_y=-N}^{+N} \sum_{q_x=-M}^{+M} A_{qy,qx} \cdot \mathrm{sinc}(2q_x, 2q_y) \cdot \delta(\omega_x - q_x\omega_{x0}, \omega_y - q_y\omega_{y0})$$

We can only capture the intensity of the wavefront as an absolute square of its amplitude. This corresponds to a convolution operation in the spectral domain by its complex conjugate spectral distribution. As mentioned above, the 0th order caused by the grating component 9 is blocked so the 2-dimensional matrix of the amplitude transfer function $A_f\ q_x,q_y$ results in:

$$A_{f\,qy,qx} = \frac{1}{8}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

The index value of “1” stands for a passing the “0” for a blocked spectral order, the position of indices for the integer diffraction order starting with an index pair of $[q_x,q_y] = [-1,-1]$ at the upper left matrix position. The prefactor of 1/8 sets the entire energy content to 1. The spectral convolution yields the intensity transfer $B_f\ q_x,q_y$ function:

$$B_{f\,qy,qx} = A_{f\,qy,qx} \otimes A^*_{f\,qy,qx} = \frac{1}{64}\begin{pmatrix} 1 & 2 & 3 & 2 & 1 \\ 2 & 2 & 4 & 2 & 2 \\ 3 & 4 & 8 & 4 & 3 \\ 2 & 2 & 4 & 2 & 2 \\ 1 & 2 & 3 & 2 & 1 \end{pmatrix}$$

This intensity transfer matrix of contains 5x5 elements due to the convolution operation, i.e. the spectrum is extended by new replicas. The value of indices stands for its part related to total energy. In [6] we described the analysis in order to reveal the phase gradient in x and y direction based on the order of spectral intensity of $\sim I_{2,0}$ and $\sim I_{0,2}$ respectively. Their corresponding spectra of index $B_{f\ 2,0}$ and $B_{f\ 0,2}$ has to be filtered out, shifted to the origin in the spectral domain and eventually inverse Fourier transformed into the spatial domain. This matrix representation of $B_f\ q_x,q_y$ allows the following conclusions: i) the fraction of this replica equals to 3/64 ≈ 4.69% referred to the total signal energy, ii) this replica is surrounded by strong adjacent "neighbors", i.e. 3/16 = 18.75%, in summary (four times stronger). This increases the possibilities of i) noise and ii) aliasing, respectively.
If the mixed order replicas are blocked as suggested in the following Eq.

$$A_{f\,qy,qx} = \frac{1}{4}\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

we increased the signal to noise ratio of our desired replica to

$$B_{f\,qy,qx} = A_{f\,qy,qx} \otimes A^*_{f\,qy,qx} = \frac{1}{16}\begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 2 & 0 & 2 & 0 \\ 1 & 0 & 4 & 0 & 1 \\ 0 & 2 & 0 & 2 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{pmatrix}$$

that is, 1/16 = 6.25%. But there still remain 2 adjacent replicas in its vicinity. The best solution might be a filter structure of

$$A_{f\,qy,qx} = \frac{1}{4}\begin{pmatrix} 1 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 1 \end{pmatrix}$$

which leads to a convolved intensity matrix of

$$B_{f\,qy,qx} = A_{f\,qy,qx} \otimes A^*_{f\,qy,qx} = \frac{1}{16}\begin{pmatrix} 1 & 0 & 2 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 4 & 0 & 2 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 2 & 0 & 1 \end{pmatrix}$$

with a replica proportion of 12.5% and zero neighborhood. But this spectrum originates only from mixed orders of x and y. This reveals only a phase gradient map along xy- and yx-direction, which complicates the integration based on x and y coordinates to determine the phase. If we permitted two captured images using two perpendicular filter positions of

$$A_{f\,qy,qx} = \frac{1}{2}\begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} + \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$

we would get 2 spectral intensities each corresponding to a 1 dimensional convolution:

$$B_{f\,qy,qx} = \frac{1}{4}\begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{pmatrix} + \frac{1}{4}\begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 2 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

The interesting replicas contains here 25% of the total signal energy without disturbances from any other close replica orders. This way the sensor captures light intensities carrying only the necessary information content. In our first experiments we applied the proposed filter structure in order to verify that only one spatially filtered image is sufficient to reconstruct successfully a 2 dimensional phase map.

3. EXPERIMENT

The new measuring method was implemented in the laboratory and compared with the measurements of a Shack Hartmann sensor (see Figure 7).

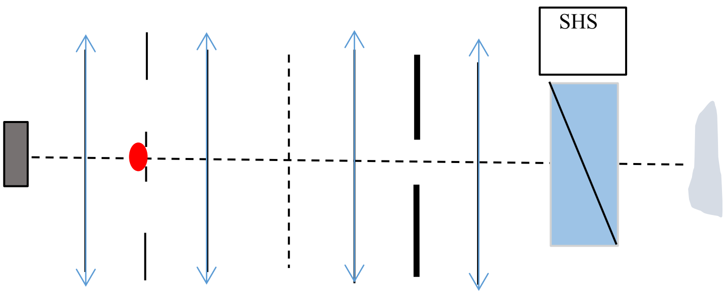

Fig7. Schematic representation of the measurement setup

An LED with a wavelength of 633 nm was used as illumination source. A nanostructured diffraction grating was used to suppress the unwanted reflections. The lenses of the 4f systems each have a focal length of 120mm. The test object was a free-form reflecting surface (see Fig. 8).
The Shack Hartmann sensor from Optocraft was used for the reference measurements.

Fig8. Freeform surface

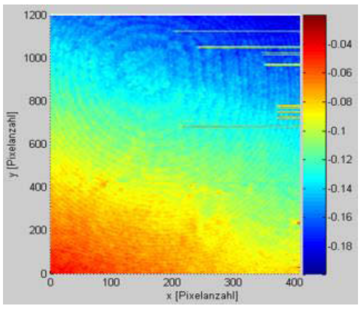

Fig9. Deviation from measurement with SHS

There was a deviation from the Shack Hartmann sensor of less than 1 μm. This confirmed the functionality of our measuring method.

4. CONCLUSION

A novel method for the measurement and characterization of optically smooth free-form surfaces in reflection was presented. The idea is an extension of the wavefront measurement principle using Fourier optical systems. The main feature of the approach is the absence of the classical beam splitter. Using nanostructured black silicon, we are able to prevent unwanted reflections. The principle and initial experimental results are presented.

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